

## Article

# Effect of Combined Application of Slow-Release and Conventional Urea on Yield and Nitrogen Use Efficiency of Rice and Wheat under Full Straw Return

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**Abstract:** The effects of one-time basal application of different mixtures of slow-release urea (SRU) and conventional urea (CU) on yield and nitrogen use efficiency (NUE) of rice and wheat were investigated to determine the appropriate ratios of SRU to CU for one-time basal fertilization in a rice–wheat rotation farmland under full residue incorporation. A field plot experiment was used in this study. Six treatments were established as follows: CK (no nitrogen fertilizer applied), T0 (100% CU, 50% applied as basal fertilizer and 50% applied as jointing fertilizer), T3 (one-time basal application of SRU and CU mixture with 30% SRU), T5 (one-time basal application of SRU and CU mixture with 50% SRU), T7 (one-time basal application of SRU and CU mixture with 70% SRU), and T10 (one-time basal application of 100% SRU). The results showed that the combined application of SRU and CU increased the yields of rice and wheat. Treatment T7 resulted in the highest rice yield, and T3 resulted in the highest wheat yield, which were 25.6% and 29.4% higher, than those of treatment T0, respectively. Compared with treatment T0 (application of CU alone), the combined application of SRU and CU resulted in 27.4–96.5% and 22.8–57.1% higher NUE in rice and wheat, respectively.

**Keywords:** slow-release urea; rice; wheat; yield; nitrogen use efficiency



**Citation:** Yu, Z.; Shen, Z.; Xu, L.; Yu, J.; Zhang, L.; Wang, X.; Yin, G.; Zhang, W.; Li, Y.; Zuo, W.; et al. Effect of Combined Application of Slow-Release and Conventional Urea on Yield and Nitrogen Use Efficiency of Rice and Wheat under Full Straw Return. *Agronomy* **2022**, *12*, 998. <https://doi.org/10.3390/agronomy12050998>

Academic Editor: David A Van Sanford

Received: 5 March 2022

Accepted: 19 April 2022

Published: 21 April 2022

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## 1. Introduction

China is a leading country in the production and use of chemical fertilizers. The fertilizer consumption per hectare of crops in China averages 328.5 kg, which is much higher than the world average (120 kg ha<sup>−1</sup>) and is 2.6 times that of the United States and 2.5 times that of European Union [1]. Excessive use of chemical fertilizers, especially nitrogen fertilizers, not only increases the cost of fertilization but also causes a large amount of surplus nitrogen to enter the environment through volatilization, leaching, nitrification, and denitrification, which results in the loss of nitrogen from the soil–crop system and leads to a series of environmental issues, such as eutrophication, greenhouse gas emissions, and soil acidification [2–4]. The average nitrogen use efficiency (NUE) in China is approximately 35%, which is approximately 70% of the global average [5]. The application of slow-release urea (SRU) is an important means to improve crop NUE, lessen the frequency and application level of fertilization, lower the cost of fertilization, and reduce the loss of nitrogen. Geng et al. [6] showed that under the same nitrogen application level, the application of SRU resulted in 6.1–8.2% higher rice yield and significantly higher NUE than did the application of conventional urea (CU). Yang et al. [7] found that the

application of SRU resulted in significantly higher wheat yield and 28.5% higher NUE than did application of CU. Some recent studies also found that the application of SRU resulted in the increases in rice and wheat yields and NUE [8,9].

Residue incorporation is also an important way to improve soil fertility, reduce the level of nitrogen fertilizer application, and improve NUE [10,11]. China is rich in crop residue resources. The Fertilizer Use Zero-Growth Action Plan by 2020 issued by the Ministry of Agriculture in 2015 clearly requires that the proportion of nutrients released by residue incorporation should reach 60% by 2020 [3]. However, the incorporation of a large amount of crop residues into the soil will inevitably change the status of the soil nitrogen supply, which may further aggravate the inadequate nitrogen supply in the early stage of crop growth under one-time basal application of SRU [12,13]. The combined application of SRU and CU can alleviate early nutrient deficiency caused by residue incorporation to a certain extent. Through field experiments, Lyu et al. [14] found that the combined application of SRU and CU could increase the yield of rice. Zheng et al. [15] showed that the combined application of SRU and CU increased the yield of wheat by 7.9–10.3% and reduced the labor cost of fertilization. Most past reports on the effects of combined application of SRU and CU on crop growth and soil fertility have focused on single-season crops. However, few studies have investigated the effects of one-time basal application of mixtures of SRU and CU on soil fertility, yield, and NUE in rice–wheat rotation systems. Therefore, there is an urgent need to determine the appropriate SRU-to-CU ratios for one-time basal fertilization in rice–wheat rotation systems under full residue incorporation.

To assess whether one-time basal fertilization can improve NUE while ensuring stability of grain crop yields in rice–wheat rotation systems, a field plot experiment was used to investigate the effects of one-time basal application of mixtures of SRU and CU on yield and NUE of rice and wheat, soil organic matter, and nitrogen nutrients. The objective of this study was to assess the feasibility of one-time basal fertilization and explore the appropriate SRU-to-CU ratios for one-time basal fertilization in rice–wheat rotation systems under full residue incorporation. The results provide a scientific basis for appropriate application of SRU to ensure food production and protect environments.

## 2. Materials and Methods

### 2.1. Experimental Site and Experimental Materials

The field experiments were conducted in Kunshan (31°49' N, 120°89' E) of Jiangsu Province, China from 2020 to 2021. The initial contents of organic matter, total nitrogen and available nitrogen were 28.4 g kg<sup>−1</sup>, 0.71 g kg<sup>−1</sup> and 120.5 mg kg<sup>−1</sup>, respectively. The wheat and rice cultivars used in this study were *Nanjing 46* and *Ningmai 13*, respectively. The conventional nitrogen fertilizer was urea, and the nitrogen content was 46%; the slow-release nitrogen fertilizer was resin coated slow-release urea with a nitrogen content of 42% and a release longevity of 90 days; The phosphate and potassium fertilizers in this study were calcium superphosphate (P<sub>2</sub>O<sub>5</sub> 12%) and potassium chloride (K<sub>2</sub>O 60%).

### 2.2. Experimental Design

Six treatments were set according to the different proportion of slow-release urea and conventional urea: CK (no nitrogen fertilizer applied), T0 (100% CU, 50% applied as basal fertilizer and 50% applied as jointing fertilizer), T3 (one-time basal application of SRU and CU mixture with 30% SRU), T5 (one-time basal application of SRU and CU mixture with 50% SRU), T7 (one-time basal application of SRU and CU mixture with 70% SRU), and T10 (one-time basal application of 100% SRU). Fertilizers were applied at the following rates: N, 300 kg ha<sup>−1</sup>, P<sub>2</sub>O<sub>5</sub>, 75 kg ha<sup>−1</sup> and K<sub>2</sub>O, 150 kg ha<sup>−1</sup> for rice; N, 240 kg ha<sup>−1</sup>, P<sub>2</sub>O<sub>5</sub>, 75 kg ha<sup>−1</sup>, and K<sub>2</sub>O, 90 kg ha<sup>−1</sup> for wheat. Among them, all phosphorus and potassium fertilizers were applied as basic fertilizer on 16 June 2020 and 14 November 2020, respectively. The jointing fertilizers of T0 treatment in rice and wheat seasons were applied on 5 July 2020 and 20 February 2021, respectively. Each experimental plot area is 20.0 m<sup>2</sup>, repeated 4 times and arranged in a randomized block design, ridges were set to separate

each plot. During planting, drainage and irrigation were carried out separately. The straw of the previous crop was returned to the field before planting. Rice was transplanted on 17 June 2020 and harvested on 29 October 2020; Wheat was sown on 16 November 2020 and harvested on 25 May 2021. The transplanting density of rice, the sowing amount of wheat and the field management measures in the growth period were consistent.

### 2.3. Soil and Plant Analysis

The top 20 cm soil samples were collected in quadruplicate from each plot at maturity. After soil samples were air-dried, all samples were crushed and sieved (1 mm and 0.150 mm) for further physicochemical analysis. Soil organic matter was determined by potassium dichromate external heating method, total nitrogen and available nitrogen were determined by semi micro Kjeldahl nitrogen determination method and alkali hydrolyzable diffusion method, respectively.

Representative 2 m<sup>2</sup> of mature rice and wheat samples from each plot were selected and harvested artificially to determine the yield, yield composition, and straw biomass. For analysis of nitrogen content of grain and straw of rice and wheat, 20-hole rice and wheat plants from each plot were randomly dug out and then dried to constant weight at 80 °C. The dried rice and wheat plants were divided into two parts: stem (including leaf) and grain, and then crushed, respectively. The nitrogen content of grain and straw was determined by H<sub>2</sub>SO<sub>4</sub>–H<sub>2</sub>O<sub>2</sub> digestion indophenol blue colorimetry.

### 2.4. Calculation and Statistical Analysis

Nitrogen accumulation (kg ha<sup>−1</sup>) = grain dry weight × grain nitrogen content + straw dry weight × nitrogen content of straw [16].

Agronomic N use efficiency (kg kg<sup>−1</sup>) = (grain yield in N application plots–grain yield in N omission plots)/the amount of applied N fertilizer [16].

The apparent recovery efficiency of N fertilizer (%) = (N accumulation in N application plots–N accumulation in N omission plots)/the amount of applied N fertilizer × 100 [16].

Partial factor productivity of applied N (kg kg<sup>−1</sup>) = grain yield in N application plots/the amount of applied N fertilizer [16].

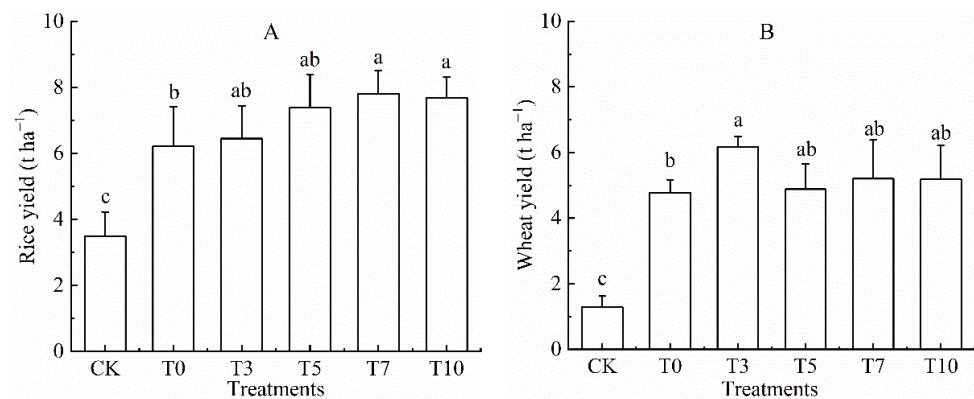
Annual nitrogen use efficiency (%) = (annual N accumulation in N application plots–annual N accumulation in N omission plots)/the amount of annual applied N fertilizer × 100.

Data processing and figures drawing were used by Origin 2018. The analysis of variance (ANOVA) for the data with the model of randomized complete block (RCB) design was used by SPSS 19.0. The least significant difference (LSD) method at  $p < 0.05$  was used to analyze the significant differences between the treatments.

## 3. Results

### 3.1. Effects of Different Fertilization Treatments on Yield and Yield Components of Rice and Wheat

One-time basal application of mixtures of SRU and CU increased the yields of rice and wheat (Figure 1). The yields of rice and wheat for treatment T0 (100% CU, SRU-to-CU ratio = 0/10) were 6.21 and 4.77 t ha<sup>−1</sup>, respectively. The rice yields of treatments T3 (SRU-to-CU ratio = 3/7), T5 (SRU-to-CU ratio = 5/5), T7 (SRU-to-CU ratio = 7/3), and T10 (100% SRU, SRU-to-CU ratio = 10/0) were 6.45, 7.38, 7.80, and 7.68 t ha<sup>−1</sup>, which were 3.9%, 18.8%, 25.6%, and 23.7% higher than the rice yield of treatment T0, respectively. Among all treatments, treatment T7 resulted in the highest rice yield, which was significantly higher than that of treatment T0. The wheat yields of treatments T3, T5, T7, and T10 were 6.17, 4.88, 5.20, and 5.18 t ha<sup>−1</sup>, which were higher than that of treatment T0 by 29.4%, 2.3%, 9.0%, and 8.6%, respectively. Treatment T3 resulted in the highest wheat yield, which was significantly higher than that of treatment T0.



**Figure 1.** Effect of different fertilization treatments on the yield of rice (A) and wheat (B). Columns with different small case letters show significant difference between different treatments at  $p < 0.05$  by LSD's multiple range test. Values are mean of four replicates and bars show standard deviation. CK, no nitrogen fertilizer applied; T0, 100% conventional urea (CU); T3, one-time basal application of slow-release urea (SRU) and CU mixture with 30% SRU; T5, one-time basal application of SRU and CU mixture with 50% SRU; T7, one-time basal application of SRU and CU mixture with 70% SRU; T10, one-time basal application of 100% SRU.

The combined application of SRU and CU increased the number of panicles and the number of grains per panicle of rice but showed no significant effect on the seed setting rate or 1000-grain weight of rice (Table 1). The number of panicles per hectare and the number of grains per panicle in treatment T0 were 223.9 and 86.1, respectively. Treatments T3, T5, T7, and T10 increased the number of panicles per hectare of rice by 8.0%, 32.2%, 51.8%, and 25.1%, and increased the number of grains per panicle by 10.2%, 6.2%, 11.5%, and 10.9%, respectively. Among these treatments, T7 resulted in the highest number of panicles per hectare, the highest number of grains per panicle, the highest seed setting rate, and the highest 1000-grain weight of rice. The combined application of SRU and CU increased the number of panicles of wheat but had no significant effect on the number of grains per panicle or 1000-grain weight of wheat. The number of panicles of wheat in treatments T3, T5, T7, and T10 were higher than that of treatment T0 by 23.6%, 5.8%, 7.4%, and 7.5%, respectively. Treatment T3 resulted in the highest number of panicles, seed setting rate, and 1000-grain weight of wheat.

**Table 1.** Effect of different fertilization treatments on yield components of rice and wheat.

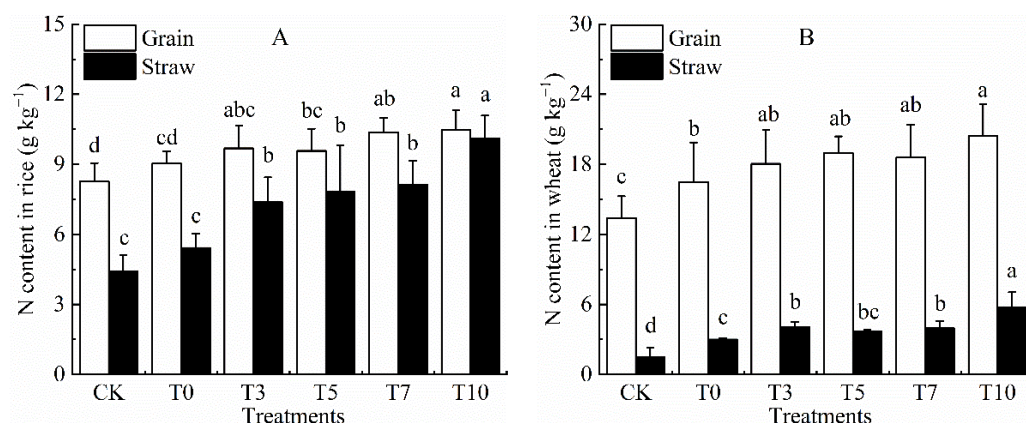
Crops	Treatments	Panicle Density (10 <sup>4</sup> ha <sup>-1</sup> )	Grain Number per Panicle	Seed Setting Rate (%)	Thousand-Grain Weight (g)
Rice	CK	168.8 ± 22.2 d	70.2 ± 11.6 b	91.5 ± 3.7 b	21.6 ± 1.2 b
	T0	223.9 ± 47.5 cd	86.1 ± 7.6 ab	95.9 ± 2.1 a	27.0 ± 1.6 a
	T3	241.9 ± 63.4 bc	94.9 ± 21.7 a	96.3 ± 1.2 a	26.5 ± 2.5 a
	T5	295.9 ± 44.8 ab	91.4 ± 10.3 a	95.8 ± 1.7 a	27.0 ± 1.5 a
	T7	339.8 ± 20.3 a	96.0 ± 8.2 a	97.3 ± 1.1 a	27.2 ± 2.7 a
	T10	280.1 ± 25.6 abc	95.5 ± 10.6 a	97.1 ± 0.3 a	27.4 ± 2.6 a
Wheat	CK	170.1 ± 14.8 c	20.5 ± 2.9 b		36.3 ± 2.0 b
	T0	310.9 ± 30.3 b	39.0 ± 0.8 a		39.4 ± 0.9 a
	T3	384.4 ± 12.8 a	39.5 ± 1.3 a		40.7 ± 0.5 a
	T5	329.0 ± 29.5 ab	37.3 ± 1.9 a		39.6 ± 1.0 a
	T7	334.0 ± 62.9 ab	38.5 ± 2.1 a		39.9 ± 1.5 a
	T10	334.2 ± 61.8 ab	38.8 ± 1.3 a		39.8 ± 0.7 a

Values are mean ± SD (standard deviation) of four replicates. Columns with different small case letters show significant difference between different treatments at  $p < 0.05$  by LSD's multiple range test. CK, no nitrogen fertilizer applied; T0, 100% conventional urea (CU); T3, one-time basal application of slow-release urea (SRU) and CU mixture with 30% SRU; T5, one-time basal application of SRU and CU mixture with 50% SRU; T7, one-time basal application of SRU and CU mixture with 70% SRU; T10, one-time basal application of 100% SRU, same below.



### 3.2. Effects of Different Fertilization Treatments on Nitrogen Uptake in Grains and Straws of Rice and Wheat

The nitrogen contents in grains and straws of rice and wheat gradually increased with increasing SRU-to-CU ratio (Figure 2). The nitrogen contents in rice grains and straws from treatment T0 were 9.03 and 5.42 g kg<sup>-1</sup>, respectively. The nitrogen contents in rice grains from treatments T3, T5, T7, and T10 were 9.68, 9.57, 10.36, and 10.48 g kg<sup>-1</sup>, respectively. The nitrogen contents in rice straws of treatments T3, T5, T7, and T10 were 7.38, 7.83, 8.13, and 10.11 g kg<sup>-1</sup>, which were higher than that of treatment T0 by 36.0%, 44.6%, 54.1%, and 86.5%, respectively.



**Figure 2.** Effect of different fertilization treatments on nitrogen uptake in grains and straws of rice (A) and wheat (B). N-nitrogen. Columns with different small case letters show significant difference between different treatments at  $p < 0.05$  by LSD's multiple range test. Values are mean of four replicates and bars show standard deviation. CK, no nitrogen fertilizer applied; T0, 100% conventional urea (CU); T3, one-time basal application of slow-release urea (SRU) and CU mixture with 30% SRU; T5, one-time basal application of SRU and CU mixture with 50% SRU; T7, one-time basal application of SRU and CU mixture with 70% SRU; T10, one-time basal application of 100% SRU.

The nitrogen contents of wheat grains and straws from treatment T0 were 16.49 and 2.99 g kg<sup>-1</sup>, respectively. The nitrogen contents in the grains of treatments T3, T5, T7, and T10 were higher than that of treatment T0 by 9.4%, 15.0%, 12.7%, and 24.0%, respectively. The nitrogen contents in the straws of treatments T3, T5, T7, and T10 were higher than that of treatment T0 by 36.1%, 23.1%, 32.8%, and 92.6%, respectively. Of these treatments, T10 resulted in the highest nitrogen contents in grains and straws of rice and wheat, which were significantly higher than those of treatment T0.

### 3.3. Effects of Different Fertilization Treatments on Nitrogen Accumulation and NUE in Rice and Wheat

Table 2 shows the effects of the combined application of SRU and CU on NUE in rice and wheat in the rice–wheat rotation farmland. The combined application of SRU and CU increased the accumulation, apparent recovery efficiency, agronomic efficiency, and partial factor productivity of nitrogen in rice. T7 resulted in significantly higher accumulation, apparent recovery efficiency, agronomic efficiency, and partial factor productivity of nitrogen in rice than those of treatment T0 by 42.1%, 69.6%, 84.7%, and 25.6%, respectively. Treatment T10 resulted in the highest accumulation and apparent recovery efficiency of nitrogen, which were higher than those of treatment T0 by 58.3% and 96.5%, respectively.

The combined application of SRU and CU increased the accumulation and apparent recovery efficiency of nitrogen in wheat but had no significant effect on the agronomic efficiency or partial factor productivity of nitrogen in wheat. Under treatment T0, the accumulation and apparent recovery efficiency of nitrogen were 87.0 kg ha<sup>-1</sup> and 28.9%, respectively. Nitrogen accumulation in wheat in treatments T3, T5, T7, and T10 was higher than in treatment T0 by 45.6%, 18.4%, 27.0%, and 42.0%, respectively. The apparent

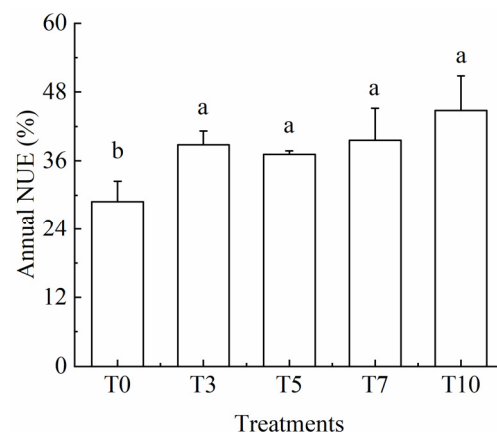
recovery efficiency of nitrogen in wheat in treatments T3, T5, T7, and T10 was higher than in treatment T0 by 57.1%, 22.8%, 33.6%, and 52.6%, respectively.

**Table 2.** Effects of different fertilization treatments on nitrogen accumulation and NUE in rice and wheat.

Crops	Treatments	N Accumulation (kg ha <sup>-1</sup> )	Agronomic N Use Efficiency (kg kg <sup>-1</sup> )	The Apparent Recovery Efficiency of N Fertilizer (%)	Partial Factor Productivity of Applied N (kg kg <sup>-1</sup> )
Rice	CK	44.8 ± 5.0 e			
	T0	113.9 ± 6.5 d	7.2 ± 1.8 b	23.0 ± 2.2 d	20.7 ± 4.0 b
	T3	132.7 ± 16.1 cd	11.4 ± 1.5 a	29.3 ± 5.4 cd	21.5 ± 3.3 ab
	T5	149.7 ± 13.9 bc	13.0 ± 3.4 a	35.0 ± 4.6 bc	24.6 ± 3.4 ab
	T7	161.9 ± 9.2 ab	13.3 ± 0.9 a	39.0 ± 3.1 ab	26.0 ± 2.3 a
	T10	180.3 ± 15.2 a	13.1 ± 1.5 a	45.2 ± 5.1 a	25.6 ± 2.1 ab
Wheat	CK	17.8 ± 4.6 c			
	T0	87.0 ± 23.6 b	14.5 ± 1.6 a	28.9 ± 3.1 b	19.9 ± 1.6 a
	T3	126.7 ± 25.4 a	20.4 ± 1.3 a	45.4 ± 3.3 a	25.7 ± 1.3 a
	T5	103.0 ± 13.4 ab	15.0 ± 3.2 a	35.5 ± 2.4 ab	20.3 ± 3.2 a
	T7	110.5 ± 27.6 ab	16.3 ± 5.8 a	38.6 ± 3.4 ab	21.7 ± 5.8 a
	T10	123.5 ± 23.7 a	16.2 ± 4.4 a	44.1 ± 3.1 ab	21.6 ± 4.4 a

Values are mean ± SD (standard deviation) of four replicates. Columns with different letters show significant difference between different treatments at  $p < 0.05$  by LSD's multiple range test. CK, no nitrogen fertilizer applied; T0, 100% conventional urea (CU); T3, one-time basal application of slow-release urea (SRU) and CU mixture with 30% SRU; T5, one-time basal application of SRU and CU mixture with 50% SRU; T7, one-time basal application of SRU and CU mixture with 70% SRU; T10, one-time basal application of 100% SRU.

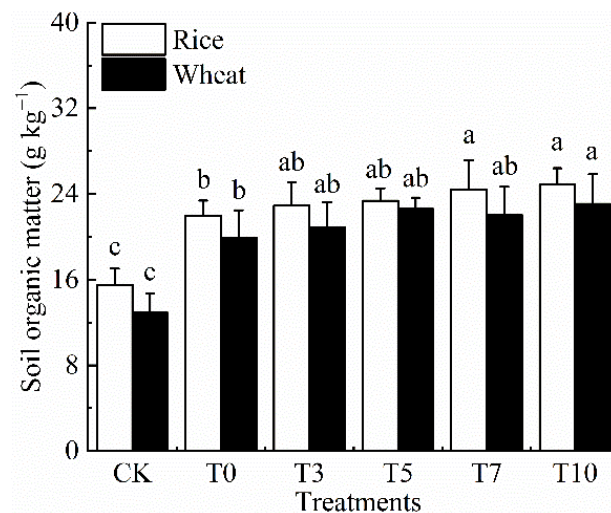
The combined application of SRU and CU increased the annual NUE, and the annual NUE showed a gradual increasing trend as the SRU-to-CU ratio increased (Figure 3). The annual NUE of the rice–wheat rotation system under treatment T0 was 28.8%, which was significantly lower than those of treatments T3, T5, T7, and T10 by 25.7%, 22.3%, 27.2%, and 35.5%, respectively. However, annual NUE was not significantly different among treatments T3, T5, T7, and T10.



**Figure 3.** Effects of different fertilization treatments on annual nitrogen use efficiency. NUE—nitrogen use efficiency. Columns with different small case letters show significant difference between different treatments at  $p < 0.05$  by LSD's multiple range test. Values are mean of four replicates and bars show standard deviation. CK, no nitrogen fertilizer applied; T0, 100% conventional urea (CU); T3, one-time basal application of slow-release urea (SRU) and CU mixture with 30% SRU; T5, one-time basal application of SRU and CU mixture with 50% SRU; T7, one-time basal application of SRU and CU mixture with 70% SRU; T10, one-time basal application of 100% SRU.

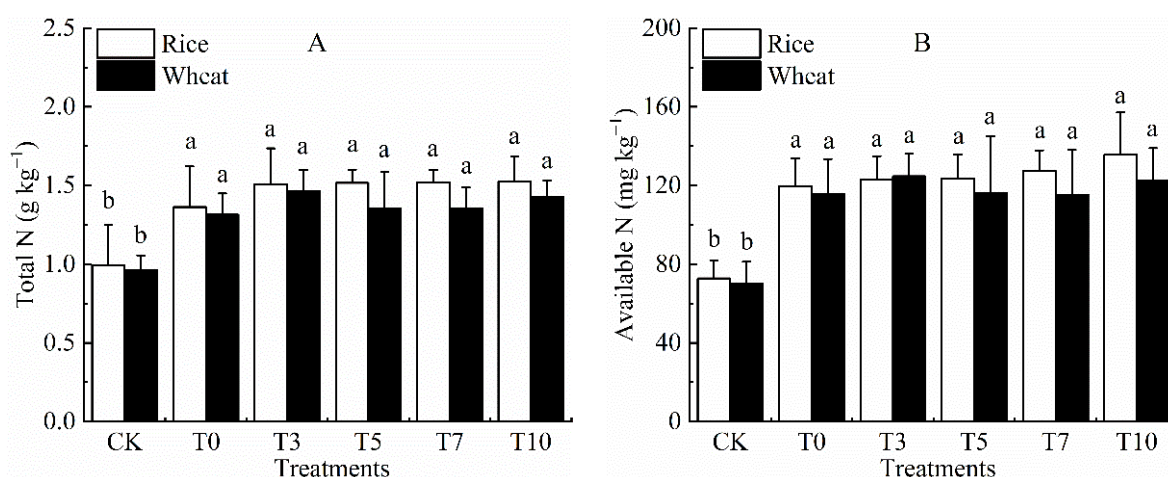
### 3.4. Effects of Different Fertilization Treatments on Soil Organic Matter, Total Nitrogen, and Available Nitrogen

The combined application of SRU and CU promoted the accumulation of soil organic matter (Figure 4). The soil organic matter content in the rice harvesting season in treatments T3, T5, T7, and T10 was higher than in treatment T0 by 4.2%, 6.3%, 11.2%, and 13.3%, respectively. The soil organic matter content in the wheat harvesting season in treatments T3, T5, T7, and T10 was higher than in treatment T0 by 4.8%, 13.4%, 10.6%, and 15.8%, respectively. Of these treatments, treatment T10 resulted in the highest soil organic matter content, which was significantly higher than that in treatment T0.



**Figure 4.** Effect of different fertilization treatments on soil organic matter content. Columns with different small case letters show significant difference between different treatments at  $p < 0.05$  by LSD's multiple range test. Values are mean of four replicates and bars show standard deviation. CK, no nitrogen fertilizer applied; T0, 100% conventional urea (CU); T3, one-time basal application of slow-release urea (SRU) and CU mixture with 30% SRU; T5, one-time basal application of SRU and CU mixture with 50% SRU; T7, one-time basal application of SRU and CU mixture with 70% SRU; T10, one-time basal application of 100% SRU.

Treatment T0 increased the total and available nitrogen content in soil of rice–wheat rotation farmland, but treatments T3, T5, T7, and T10 did not significantly affect total and available nitrogen content (Figure 5). The contents of soil total nitrogen and available nitrogen in the rice harvesting season in treatments T0, T3, T5, T7, and T10 were higher than in the control without nitrogen application (CK) by 37.1–53.6% and 64.5–86.4%, respectively. The contents of soil total nitrogen and available nitrogen in the wheat harvesting season in treatments T0, T3, T5, T7, and T10 were higher than in the control without nitrogen application (CK) by 36.7–52.3% and 64.5–77.5%, respectively. However, the contents of soil total nitrogen and available nitrogen were not significantly different among treatments T0, T3, T5, T7, and T10 in either rice harvesting season or wheat harvesting season. Treatment T10 resulted in the highest contents of soil total nitrogen and available nitrogen in the rice harvesting season, and treatment T3 resulted in the highest contents of soil total nitrogen and available nitrogen in the wheat harvesting season.



**Figure 5.** Effect of different fertilization treatments on the content of total nitrogen (A) and available nitrogen (B) in soil. Columns with different small case letters show significant difference between different treatments at  $p < 0.05$  by LSD's multiple range test. Values are mean of four replicates and bars show standard deviation. CK, no nitrogen fertilizer applied; T0, 100% conventional urea (CU); T3, one-time basal application of slow-release urea (SRU) and CU mixture with 30% SRU; T5, one-time basal application of SRU and CU mixture with 50% SRU; T7, one-time basal application of SRU and CU mixture with 70% SRU; T10, one-time basal application of 100% SRU.

#### 4. Discussion

Under full residue incorporation in the rice–wheat rotation system, the combined application of SRU and CU is beneficial in increasing yields of rice and wheat. SRU prolongs fertilizer efficiency by reducing the nutrient release rate, provides nutrients to crops for a long period of time, promotes crop growth and development, and increases plant height, stem diameter, leaf area index, and dry matter accumulation, thereby providing a good basis for crop yield [12,17,18]. Lyu et al. [19] showed that the combined application of SRU and CU could increase the yield of rice, and 60% of SRU in the mixture was the best and worthy of promotion. In our study, the mixture with 70% SRU resulted in the highest yield of rice, which is consistent with the results of Wang et al. [20], who showed that the application of a mixture of SRU and CU with 70% SRU could increase rice yield by 26.6%. The results of Zhang et al. [21] on wheat crops showed that the comprehensive effect of mixtures of SRU and CU with 20–40% SRU resulted in the highest winter wheat yield and NUE, which is generally consistent with our finding that the mixture of SRU and CU with 30% SRU resulted in the highest wheat yield. Fan et al. [22] have also confirmed that the combined application of SRU and CU can increase the yield of wheat, with 75% SRU resulting in the highest yield in their study. In our study, under full residue incorporation, crop residue decomposition likely competed with wheat growth for nitrogen in the early growth stage [23]. Therefore, the ratio of CU to SRU must be increased to meet the demand for nitrogen by crop residue decomposition and wheat growth in the early growth stage. In this study, the optimal ratio of SRU to CU in the rice season was higher than that in the wheat season, perhaps because sufficient availability of water and heat in the rice season are conducive to the release and transport of SRU nutrients and the decomposition of the residue of the previous crop, allowing higher ratios of SRU to CU [24,25]. However, the low temperature and low rainfall in the wheat season are not conducive to the release of SRU and the decomposition of crop residue, so higher ratios of CU to SRU is generally required to meet the demand for nitrogen by crop residue decomposition and wheat growth in the early growth stage [26–28].

The combined application of SRU and CU increases the uptake and utilization of nitrogen by rice and wheat plants. The combined application of SRU and CU results in significantly higher NUE of rice and wheat. The application of SRU synchronizes nutrient release and supply with crop nutrient uptake, maintains a dynamic balance



between nutrient supply intensity and crop physiological demand, and reduces the risk of loss of surplus nitrogen from the soil, thereby improving the uptake and utilization of nitrogen by crops [29–31]. Fu et al. [32] showed that the application of slow-release nitrogen fertilizers could increase the NUE of early rice and late rice by 13.6–86.4% and 100–161.4%, respectively. Haerlein et al. [33] showed that the application of SRU increased the NUE of spring wheat by 4.2% within the entire SRU application range of 25–100 kg ha<sup>−1</sup>. One-time basal application of mixtures of SRU and CU reduces the risk of leaching loss caused by the excessively rapid release of nutrients from urea and simultaneously solves the problem that the slow-release rate of nutrients from SRU cannot meet the nitrogen demand of crops in the early growth stage and the potential problem of nitrogen supply shortage in the late growth stage [34,35].

Under full residue incorporation, the combined application of SRU and CU resulted in higher soil organic matter contents than that of treatment T0 by 4.2–15.8%, perhaps because the application of SRU increased the accumulation of carbon sources in the soil by increasing aboveground biomass due to improved uptake and utilization of nutrients by crops, enhancing microbial activity and promoting the growth of crop roots [36]. In our study, the combined application of SRU and CU increased the total nitrogen and available nitrogen contents in the soil. Past research has found that slow-release nitrogen fertilizers can significantly reduce the loss of nitrogen through ammonia volatilization and the proportion of ammonia volatilization is negatively correlated with the proportion of SRU in the combined application [37,38]. Guo et al. [39] found that the mixed application of slow-release nitrogen fertilizer and urea could effectively reduce the loss of nitrogen through ammonia volatilization and nitrogen leaching and retain the available nitrogen in the topsoil for a prolonged period. In addition, the application of SRU increases soil enzyme activity [40], which, in turn, enhances organic matter decomposition and biological nitrogen fixation and ultimately improves soil fertility [41].

## 5. Conclusions

This study has confirmed that higher yields of rice and wheat can be achieved through one-time basal application of SRU and CU under full residue incorporation in the rice–wheat rotation farmland. Yields of rice and wheat in all treatments with different SRU-to-CU ratios were higher than that in conventional 100% CU treatments, and the maximum increments were found in the treatments with 70% SRU in rice season and 30% SRU in wheat season, respectively. The combined application of SRU and CU increased the uptake and utilization of nitrogen in rice and wheat, and the NUE of rice and wheat was highest in the treatments with 100% SRU and 30% SRU, respectively. In addition, One-time basal application of SRU and CU increased the contents of soil organic matter, total nitrogen and available nitrogen in the rice–wheat rotation farmland, thereby improved soil fertility.

**Author Contributions:** Conceptualization and funding acquisition, Y.S., Z.H., Y.B., and G.Y.; Z.Y., Z.S., and L.X. conducted experiments; J.Y., L.Z., and X.W. contributed new reagents or analytical tools. W.Z. (Wengang Zuo), Y.L., and W.Z. (Wenjie Zhang) analyzed data. Z.Y. wrote the manuscript. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by National key research and development project Foundation of China (2018YFD030800), Research Fund for Jiangsu Agricultural Industry Technology System (JATS [2021]348, JATS [2021]349, and JATS [2021]350).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Conflicts of Interest:** Not applicable.

## References

- Ministry of Agriculture and Rural Affairs of the People's Republic of China. Fertilizer Use Zero-Growth Action Plan by 2020. 2015. Available online: [http://www.moa.gov.cn/nybg/b/2015/san/201711/t20171129\\_5923401.htm](http://www.moa.gov.cn/nybg/b/2015/san/201711/t20171129_5923401.htm) (accessed on 18 March 2015).
- Aschonitis, V.G.; Salemi, E.; Colombani, N.; Castaldelli, G.; Mastrocicco, M. Formulation of Indices to Describe Intrinsic Nitrogen Transformation Rates for the Implementation of Best Management Practices in Agricultural Lands. *Water Air Soil Poll.* **2013**, *224*, 1489. [\[CrossRef\]](#)
- Dong, Y.; Yang, J.; Zhao, X.; Yang, S.; Mulder, J.; Dörsch, P.; Peng, X.; Zhang, G. Soil acidification and loss of base cations in a subtropical agricultural watershed. *Sci. Total Environ.* **2022**, *827*, 154338. [\[CrossRef\]](#) [\[PubMed\]](#)
- The National Academies Press. *Reducing the Health Impacts of the Nitrogen Problem: Proceedings of a Workshop in Brief*; The National Academies Press: Washington, DC, USA, 2021. [\[CrossRef\]](#)
- Fan, M.; Shen, J.; Yuan, L.; Jiang, R.; Chen, X.; Davies, W.; Zhang, F. Improving crop productivity and resource use efficiency to ensure food security and environmental quality in China. *J. Exp. Bot.* **2012**, *63*, 13–24. [\[CrossRef\]](#) [\[PubMed\]](#)
- Geng, J.; Sun, Y.; Zhang, M.; Li, C.; Yang, Y.; Liu, Z.; Li, S. Long-term effects of controlled release urea application on crop yields and soil fertility under rice-oilseed rape rotation system. *Field Crop. Res.* **2015**, *184*, 65–73. [\[CrossRef\]](#)
- Yang, Y.; Zhang, M.; Zheng, L.; Cheng, D.; Liu, M.; Geng, Y. Controlled release urea improved nitrogen use efficiency, yield, and quality of wheat. *Agron. J.* **2011**, *103*, 479–485. [\[CrossRef\]](#)
- Gil-Ortiz, R.; Ángel Naranjo, M.; Ruiz-Navarro, A.; Atares, S.; García, C.; Zotarelli, L.; Bautista, A.S.; Vicente, O. Enhanced agronomic efficiency using a new controlled-released, polymeric-coated nitrogen fertilizer in rice. *Plants* **2020**, *9*, 1183. [\[CrossRef\]](#) [\[PubMed\]](#)
- Ghafoor, I.; Habib-ur-Rahman, M.; Ali, M.; Afzal, M.; Ahmed, W.; Gaiser, T.; Ghaffar, A. Slow-release nitrogen fertilizers enhance growth, yield, NUE in wheat crop and reduce nitrogen losses under an arid environment. *Environ. Sci. Pollut. R.* **2021**, *28*, 43528–43543. [\[CrossRef\]](#) [\[PubMed\]](#)
- Zhou, Y.; Zhang, Y.; Tian, D.; Mu, Y. The influence of straw returning on N<sub>2</sub>O emissions from a maize-wheat field in the North China Plain. *Sci. Total Environ.* **2017**, *584*, 935–941. [\[CrossRef\]](#) [\[PubMed\]](#)
- Zhao, S.; He, P.; Qiu, S.; Jia, L.; Liu, M.; Jin, J.; Johnston, A.M. Long-term effects of potassium fertilization and straw return on soil potassium levels and crop yields in north-central China. *Field Crop. Res.* **2014**, *169*, 116–122. [\[CrossRef\]](#)
- Yang, Y.; Liu, B.; Ni, X.; Tao, L.; Yu, L.; Yang, Y.; Feng, M.; Zhong, W.; Wu, Y. Rice productivity and profitability with slow-release urea containing organic-inorganic matrix materials. *Pedosphere* **2021**, *31*, 511–520. [\[CrossRef\]](#)
- Alijani, K.; Bahrani, M.J.; Kazemeini, S.A. Short term response of soil and wheat yield to tillage, corn residue management and nitrogen fertilization. *Soil Till. Res.* **2012**, *124*, 78–82. [\[CrossRef\]](#)
- Lyu, T.; Shen, J.; Ma, J.; Ma, P.; Yang, Z.; Dai, Z.; Zheng, C.; Li, M. Hybrid rice yield response to potted-seedling machine transplanting and slow-release nitrogen fertilizer application combined with urea topdressing. *Crop J.* **2021**, *9*, 915–923. [\[CrossRef\]](#)
- Zheng, W.; Zhang, M.; Liu, Z.; Zhou, H.; Lu, H.; Zhang, W.; Yang, Y.; Li, C.; Chen, B. Combining controlled-release urea and normal urea to improve the nitrogen use efficiency and yield under wheat-maize double cropping system. *Field Crop. Res.* **2016**, *197*, 52–62. [\[CrossRef\]](#)
- Wei, H.; Hu, L.; Zhu, Y.; Xu, D.; Zheng, L.; Chen, Z.; Hu, Y.; Cui, P.; Guo, B.; Dai, Q.; et al. Different characteristics of nutrient absorption and utilization between inbred japonica super rice and inter-sub-specific hybrid super rice. *Field Crop. Res.* **2018**, *218*, 88–96. [\[CrossRef\]](#)
- Zhu, L.; Zhang, W. Effects of controlled-release urea combined with conventional urea on nitrogen uptake, root yield, and quality of *Platycodon grandiflorum*. *J. Plant Nutr.* **2017**, *40*, 662–672. [\[CrossRef\]](#)
- Wang, L.; Xue, C.; Pan, X.; Chen, F.; Liu, Y. Application of controlled-release urea enhances grain yield and nitrogen use efficiency in irrigated rice in the yangtze river basin China. *Front. Plant Sci.* **2018**, *9*, 999. [\[CrossRef\]](#)
- Lyu, Y.; Yang, X.; Pan, H.; Zhang, X.; Cao, H.; Ulgiati, S.; Wu, J.; Zhang, Y.; Wang, G.; Xiao, Y. Impact of fertilization schemes with different ratios of urea to controlled release nitrogen fertilizer on environmental sustainability, nitrogen use efficiency and economic benefit of rice production: A study case from Southwest China. *J. Clean. Prod.* **2021**, *293*, 126198. [\[CrossRef\]](#)
- Wang, H.; Li, Y.; Sun, Y.; Li, Y.; Jiang, M.; Wang, C.; Zhao, J.; Sun, Y.; Xu, H.; Yan, F.; et al. Effects of slow-release urea on nitrogen utilization and yield in mechanically-transplanted rice under different nitrogen application rates. *Chin. J. Rice Sci.* **2017**, *31*, 50–64. [\[CrossRef\]](#)
- Zhang, J.; Li, B.; Wang, C.; Luo, J.; Gu, J.; Long, S.; He, J.; Xiang, H.; Yin, B. Effects of controlled release blend bulk urea on the yield and nitrogen use efficiency of wheat and rice. *Chin. J. Rice Sci.* **2017**, *31*, 288–298. [\[CrossRef\]](#)
- Fan, Z.; Chen, J.; Zhai, S.; Ding, X.; Zhang, H.; Sun, S.; Tian, X. Optimal blends of controlled-release urea and conventional urea improved nitrogen use efficiency in wheat and maize with reduced nitrogen application. *J. Soil Sci. Plant Nut.* **2021**, *21*, 1103–1111. [\[CrossRef\]](#)
- Wu, X.; Zhang, T.; Wang, X.; Wang, X.; Zhao, J.; Wang, L.; Yang, D.; Li, G.; Xiu, W. Effects of chemical fertilizer reduction combined with application of organic fertilizer and straw on fluvo-aquic soil aggregate distribution and stability in north China. *Ecol. Environ. Sci.* **2020**, *29*, 933–941. (In Chinese) [\[CrossRef\]](#)
- Li, R.; Gao, Y.; Chen, Q.; Li, Z.; Gao, F.; Meng, Q.; Li, T.; Liu, A.; Wang, Q.; Wu, L.; et al. Blended controlled-release nitrogen fertilizer with straw returning improved soil nitrogen availability, soil microbial community, and root morphology of wheat. *Soil Till. Res.* **2021**, *212*, 105045. [\[CrossRef\]](#)

25. Wang, C.; Xiao, R.; Guo, Y.; Wang, Q.; Cui, Q.; Xiu, Y.; Ma, Z.; Zhang, M. Changes in soil microbial community composition during *Phragmites australis* straw decomposition in salt marshes with freshwater pumping. *Sci. Total Environ.* **2021**, *762*, 143996. [[CrossRef](#)] [[PubMed](#)]
26. Rajala, A.; Peltonen-Sainio, P. Slow-release fertilizer to increase grain N content in spring wheat. *Agr. Food Sci.* **2013**, *22*, 318–324. [[CrossRef](#)]
27. Kochba, M.; Gambash, S.; Avnimelech, Y. Studies on slow release fertilizers: 1. Effects of temperature, soil moisture, and water vapor pressure. *Soil Sci.* **1990**, *149*, 339–343. [[CrossRef](#)]
28. Chen, R.; Senbayram, M.; Blagodatsky, S.; Myachina, O.; Dittert, K.; Lin, X.; Balagodatsky, E.; Kuzyakov, Y. Soil C and N availability determine the priming effect: Microbial N mining and stoichiometric decomposition theories. *Global Change Biol.* **2014**, *20*, 2356–2367. [[CrossRef](#)] [[PubMed](#)]
29. Naz, M.Y.; Sulaiman, S.A. Slow release coating remedy for nitrogen loss from conventional urea: A review. *J. Control. Release* **2016**, *225*, 109–120. [[CrossRef](#)] [[PubMed](#)]
30. Ye, H.; Li, H.; Wang, C.; Yang, J.; Huang, G.; Meng, X.; Zhou, Q. Degradable polyester/urea inclusion complex applied as a facile and environment-friendly strategy for slow-release fertilizer: Performance and mechanism. *Chem. Eng. J.* **2020**, *381*, 122704. [[CrossRef](#)]
31. Azeem, B.; KuShaari, K.; Man, Z.B.; Basit, A.; Thanh, T.H. Review on materials & methods to produce controlled release coated urea fertilizer. *J. Control. Release* **2014**, *181*, 11–21. [[CrossRef](#)]
32. Fu, J.; Zhu, Y.; Jiang, L. Use of controlled release fertilizer for increasing N efficiency of direct seeding rice. *Pedosphere* **2001**, *11*, 333–339.
33. Haderlein, L.; Jensen, T.L.; Dowbenko, R.E.; Blaylock, A.D. Controlled release urea as a nitrogen source for spring wheat in western Canada: Yield, grain N Content, and N use efficiency. *Sci. World J.* **2001**, *1*, 114–121. [[CrossRef](#)]
34. Geng, J.; Chen, J.; Sun, Y.; Zheng, W.; Tian, X.; Yang, Y.; Li, C.; Zhang, M. Controlled release urea improved nitrogen use efficiency and yield of wheat and corn. *Agron. J.* **2016**, *108*, 1666–1673. [[CrossRef](#)]
35. Rnsom, C.J.; Jolley, V.D.; Blair, T.A.; Sutton, L.E.; Hopkins, B.G. Nitrogen release rates from slow- and controlled-release fertilizers influenced by placement and temperature. *PLoS ONE* **2020**, *15*, e0234544. [[CrossRef](#)]
36. Zhong, W.; Gu, T.; Wang, W.; Zhang, B.; Lin, X.; Huang, Q.; Shen, W. The effects of mineral fertilizer and organic manure on soil microbial community and diversity. *Plant Soil* **2010**, *326*, 511–522. [[CrossRef](#)]
37. Li, P.; Lu, J.; Wang, Y.; Wang, S.; Hussain, S.; Ren, T.; Cong, R.; Li, X. Nitrogen losses, use efficiency, and productivity of early rice under controlled-release urea. *Agr. Ecosyst. Environ.* **2018**, *251*, 78–87. [[CrossRef](#)]
38. Liu, X.; Chen, L.; Hua, Z.; Mei, S.; Wang, P.; Wang, S. Comparing ammonia volatilization between conventional and slow-release nitrogen fertilizers in paddy fields in the Taihu Lake region. *Environ. Sci. Pollut. R.* **2020**, *27*, 8386–8394. [[CrossRef](#)]
39. Guo, J.; Fan, J.; Zhang, F.; Yan, S.; Zheng, J.; Wu, Y.; Li, J.; Wang, Y.; Sun, X.; Liu, X.; et al. Blending urea and slow-release nitrogen fertilizer increases dryland maize yield and nitrogen use efficiency while mitigating ammonia volatilization. *Sci. Total Environ.* **2021**, *790*, 148058. [[CrossRef](#)]
40. Guan, G.; Tu, S.; Yang, J.; Zhang, J.; Yang, L. The effects of slow-release nitrogen fertilization models on soil biological properties in rice-wheat cropping system. *J. Food Agri. Environ.* **2010**, *8*, 741–746.
41. Nishino, S.F.; Spain, J.C. Biodegradation of 3-nitrotyrosine by *Burkholderia* sp. strain JS165 and *Variovorax paradoxus* JS171. *Appl. Environ. Microb.* **2006**, *72*, 1040–1044. [[CrossRef](#)]